

Pervaporation Separation of Ethyl Butyrate/Water Mixture: Experimental and Mass Transfer Investigation

Toraj Mohammadi^{*1}, Tavan Kikhavani²

Research Lab for Advanced Separation Processes, Department of Chemical Engineering, Iran University of Science and Technology, Iran

^{*1}torajmohammadi@iust.ac.ir; ²kikhavani@iust.ac.ir

Abstract

In this study pervaporation (PV) of ethyl butyrate (ETB)/water mixtures using synthesized poly (ether-block-amide) (PEBA) membranes was investigated. The membranes were made via solution casting on water surface (as non solvent). After studying the effects of different parameters on the membranes morphology, it was found that the mixture of (1 n-butanol/ 3 iso-propyl alcohol), temperature range from 70-80°C and polymer concentration range from 4-7 wt could be used to obtain uniform membranes. PV separation of ETB/water mixtures was carried out using these membranes. The results showed that with increasing ETB concentration, both total permeation flux and ETB separation factor increase. Increasing temperature, in the studied limited range, resulted in decreasing separation factor and increasing permeation flux. With decreasing permeate pressure, permeation flux increased and separation factor decreased.

Overall mass transfer coefficient was evaluated using steady state ETB permeation flux equation. Membrane mass transfer coefficient, boundary layer thickness and liquid boundary layer mass transfer coefficient were calculated using the modified concentration polarization equation and the resistance in series model. Concentration polarization index (using membrane and liquid boundary layer mass transfer coefficients) was defined and used to present extent of the concentration polarization phenomenon.

The modified Arrhenius model was used to correlate ETB permeation flux and the operating temperature. Good agreement was observed between the experimental results and the model predictions. Results showed that the effect of temperature on sorption is greater than that on diffusion.

Keywords

ETB/Water Separation; Pervaporation; PEBA Membrane; Mass Transfer Coefficient; Concentration Polarization

Introduction

Membrane separation processes have been investigated for long time in various applications. The rapid development of these processes is due to their environmental friendly properties, energy saving aspects, effective recovery and separation of volatile organic components. They have different industrial applications such as food, chemical, petrochemical (CO₂ capture and separations) and so on. Pervaporation (PV) process has a good potential for separating liquid mixtures of volatile ingredients. PV can be used for concentration or recovery of organics from aqueous solutions (Li et al. 2008), separation of organic mixtures (Sridhar et al. 2004) and so on.

Aroma compounds in juice which are responsible for a typical juice flavor are very sensitive to heat, thus conventional processes that involve evaporation may cause loss of these compounds and change the juice flavors. Therefore, these aroma compounds should be recovered with process such as PV, which can conserve them without any loss.

In this study, synthesized poly (ether-block-amide) (PEBA) membranes were used for recovery of ETB/water mixtures. The PEBA membranes were prepared via casting solution method. At first, the effects of different parameters, such as ratio of solvents, temperature and concentration of polymeric solution were investigated on membrane formation. After that, the prepared membranes were evaluated in PV process. Finally, the overall, membrane and liquid boundary layer mass transfer coefficients were calculated and the extent of concentration polarization was predicted. Modified Arrhenius model was used to correlate ETB permeation flux and operate temperature and the effects of temperature on

separation mechanism (sorption and diffusion) were studied in details.

Experimental

Materials

PEBA (as granule) was supplied by Atochem Company. n-Butanol (74.12 g/mol, 0.812 g/cm³), isopropyl alcohol (60.1 g/mol, 0.786 g/cm³, max. 0.005% H₂O) and ETB (for synthesis, 116.16 g/mol, 0.88 g/cm³) were purchased from Merck Chemical Company. The microporous polysulfone (PS) membranes [ultrafiltration (UF) pHT20-6338] were used as support layer, provided by Dow Denmark, Inc. Physical and thermodynamic properties of ETB are given in Table 1.

TABLE 1 PHYSICAL AND THERMODYNAMIC PROPERTIES OF ETB
(Seeaders 1998; Perry 1999; Lyman 1990)

Vapor pressure (pa)		2038
Infinite dilute diffusion coefficient (m ² /s)		7.4×10^{-10}
Infinite dilute activity coefficient		1161
Henry law constant (pa/mol fraction)		2366118
Antoine constants	A	20.987
	B	3202.2
	C	56.6985

Membrane Preparation

PEBA membranes were prepared by casting the polymeric solution (PEBA + solvents) on the non-solvent (water) surface. Due to the solvent and non-solvent exchange, thin PEBA films were formed on the non-solvent surface. The PEBA membranes were put on the UF membranes (as support layers) for providing their mechanical strength. The details of membrane preparation and mechanism of membrane formation were described in our previous work (Mohammadi et al. 2008).

PV Setup and Experiments

PV apparatus used for PV experiments is presented in Fig.1. The upstream pressure was maintained at atmospheric pressure (using air release valve) and the downstream pressure was kept low with a vacuum pump. The amount of feed temperature and downstream pressure were recorded by thermostat and monometer, respectively. Permeation fluxes collected over a given period of time in a cold trap were weighed using a digital balance (PRECISA M310)

with an accuracy of about 0.001 gr and analyzed using gas chromatography (GC-2010 Shimadzu).

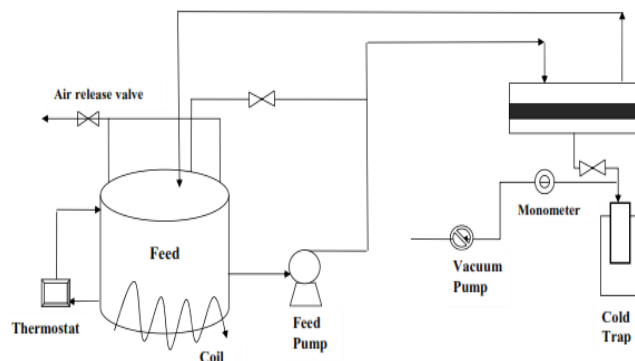
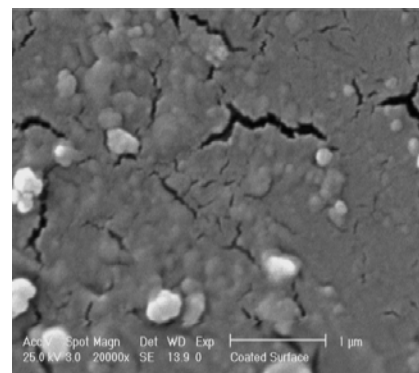


FIG. 1 SCHEME OF THE LABORATORY SCALE PV SETUP

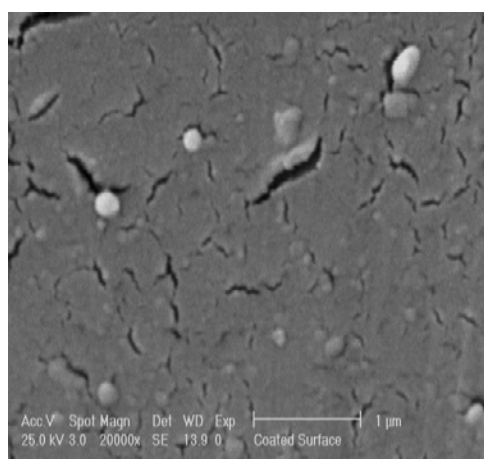
Results and Discussion

Membrane Formation

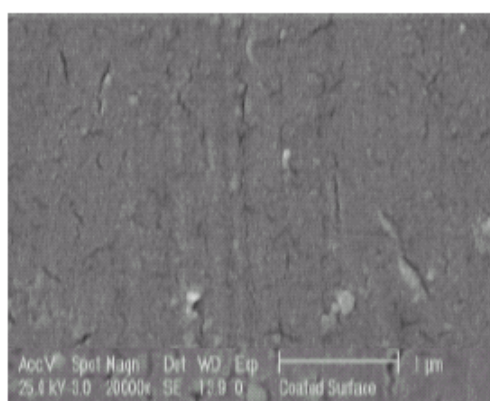
After dripping the polymeric solution on the water surface, because of the difference between polymeric solution and water surface tension, the polymeric solution was spontaneously spread on the water surface, and after the mutual diffusion of solution and non-solvent the thin membrane film was obtained. The influences of different parameters such as ratio of solvents, polymeric solution concentration and temperature on membrane formation were investigated. The SEM photographs of PEBA membranes that synthesized at different solvents ratio are shown in Fig. 2. As it can be observed that addition of iso-propanol improves the surface quality. With 1n- Butanol / 3 iso-propanol ratio, (Fig. (2.D)), the defect-free membranes can be obtained and high separation performance can be achieved. High quality films were obtained in a (3/1) ratio of iso-propanol / n- Butanol, temperature range from 60-80°C and polymer concentration range from 4-7 wt%. The effects of different parameters on the membrane formation were described in details in our previous work (Mohammadi et al. 2008).



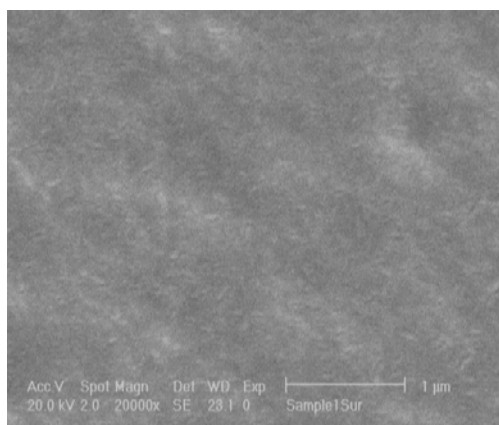
(A)



(B)



(C)



(D)

FIG. 2 SEM PHOTOGRAPHS OF THE MEMBRANES USING DIFFERENT SOLVENT RATIOS AT 75°C

A: N-BUTANOL, B: 3 N-BUTANOL / 1 ISO-PROPANOL, C: 1 N-BUTANOL / 1 ISO-PROPANOL, D: 1N-BUTANOL / 3 ISO-PROPANOL

PV Experiments

PV experiments were carried out to separate ETB/water mixtures. The effects of feed concentration on permeation flux and separation factor is shown in Fig. 3. As observed, total permeation flux and ETB separation factor

increase with increasing feed concentration. This can be described with enhancement of the liquid activity and the driving force for ETB transport. The effect of temperature on total permeation flux and ETB separation factor is shown in Fig. 4. With increasing temperature, total permeation flux increases but ETB separation factor decreases. Mobility of the polymer chains increases with increasing temperature, therefore the permeation flux of both ETB and water increase. Thus, ETB separation factor (the ratio of two permeation fluxes) decreases. The effect of permeate pressure on ETB permeation flux and separation factor is shown in Fig. 5. With decreasing permeate pressure, ETB permeation flux slightly increases, while ETB separation factor decreases. ETB is the organic compound with the high Henry's law constant. With decreasing the permeate pressure, ETB permeation flux increases slower than water permeation flux. Since low vacuum pressure is costly and also has negligible effect on ETB PV separation performance, in addition for recovery of ETB (with high saturated vapor pressure and high activity coefficient), a relatively high vacuum pressure is preferred (Hwang and She 2004).

Investigation of Mass Transfer Phenomenon

PV can be classified into three categories, i.e. vacuum driven; temperature-gradient driven and carrier gas driven, although the common process is vacuum pressure driving force. In PV system, the molecular sizes of feed components are not so different that separation can be carried out based on molecular sieving. Therefore, porous membranes cannot be used and dense membranes are more applicable. As a result, separation occurs via solution-diffusion mechanism. This mechanism consists of sorption, diffusion and desorption steps (Jiratananon et al. 2002). PV has two potential sources of selectivity. The first one is the difference between permeabilities across the membrane which means one component in the feed mixture is more soluble or diffuses more rapidly through the membrane. The second one, such as one-stage distillation, is the relative volatility of one component in the liquid mixture. Therefore selectivity can be written as below (Cussler 2007):

$$\alpha = \left[\frac{D_1 H_1}{D_2 H_2} \right] \left[\frac{H_1'}{H_2'} \right] \quad (1)$$

Where, α , D , H , H' are selectivity, diffusion coefficient, Henry law constant and partition factor, respectively. The first and the second parts in Equation 1 come from the first (difference between permeabilities across the membrane) and the second (relative volatility of one

component in the liquid mixture) potential sources of PV, respectively.

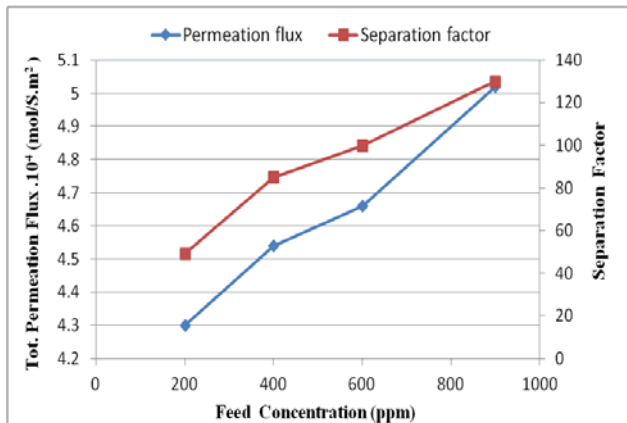


FIG. 3 EFFECT OF FEED CONCENTRATION ON TOTAL PERMEATION FLUX AND SEPARATION FACTOR AT 25°C

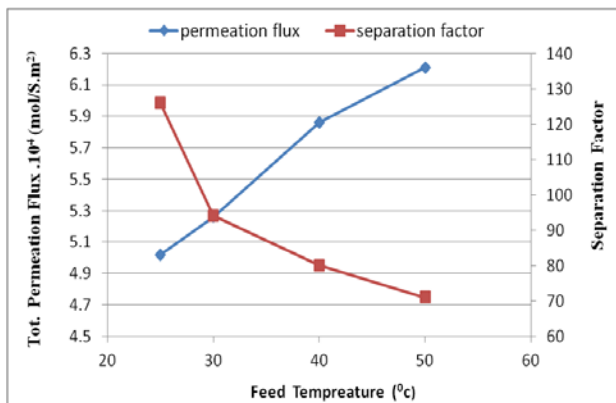


FIG. 4 EFFECT OF FEED TEMPREATURE ON TOTAL PERMEATION FLUX AND SEPARATION FACTOR 900 PPM

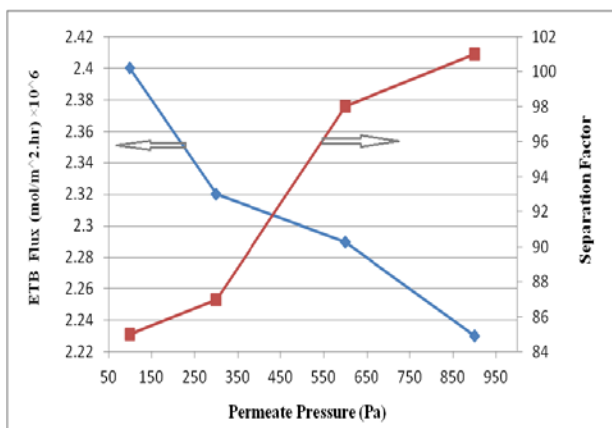


FIG. 5 EFFECT OF PERMEATE PERESSURE ON ETB PERMEATION FLUX AND SEPARATION FACTOR AT 400 PPM

Total permeation flux is the sum of ETB and water flux across the membrane:

$$\begin{aligned} J_t &= J_w + J_E \\ J_E &= J_t \cdot y_E \\ J_w &= J_t \cdot y_w \end{aligned} \quad (2)$$

Where, J_t , J_E , J_w , y_E , y_w are total permeation flux, ETB permeation flux, water permeation flux, ETB mole fraction and water mole fraction in gas phase, respectively. For a dilute solution, if the organic concentration in the permeate side is still low, separation factor can be written as bellow:

$$\alpha = \left[\frac{y_E}{y_w} \right] / \left[\frac{x_E}{x_w} \right] \cong \frac{y_E}{x_E} \cong \frac{C_{EP}}{C_{Ef}} \quad (3)$$

Where, x_E , x_w are ETB and water mole fraction in feed and C_{Ef} , C_{EP} are ETB concentrations in the feed and permeate side, respectively. The ETB and water fluxes can be written based on the non-equilibrium thermodynamic equations. For this binary system (ETB and water), fluxes can be calculated by the following equations (Hwang and She 2004; Jiratananon et al. 2002):

$$J_E = \frac{Q_E P_E^{sat}}{l} (x_E \gamma_E^\infty - \frac{P_E}{P_E^{sat}}) = \frac{Q_E}{l} (x_E \gamma_E^\infty P_E^{sat} - P_E) \quad (4)$$

$$J_w = \frac{Q_w P_w^{sat}}{l} (x_w - \frac{P_w}{P_w^{sat}}) = \frac{Q_w}{l} (P_w^{sat} - P_w) \quad (5)$$

Where, Q , P^{sat} and l are overall permeability, saturated vapor pressure and membrane thickness, respectively. $(x_E \gamma_E^\infty P_E^{sat} - P_E)$ and $(P_w^{sat} - P_w)$ are driving forces for ETB and water transfer through the membrane, respectively. Furthermore, ETB flux can be described by mass transfer coefficients as follows (Hwang and She 2006):

$$\begin{aligned} J_E &= K_E (C_{Ef} - \frac{P C_{Ep}}{H_E}) = k_{El} (C_{Ef} - C_{Em}) = \\ &k_{Em} (C_{Em} - \frac{P C_{Ep}}{H_E}) = C_{EP} \cdot q \end{aligned} \quad (6)$$

Where, K_E , k_{El} , k_{Em} , C_{Em} and q are ETB Overall mass transfer coefficient, ETB mass transfer coefficient in liquid boundary layer, ETB mass transfer coefficient in the membrane active layer, ETB concentration within the membrane and total volume flux, respectively.

Overall mass transfer coefficient can be estimated by plotting ETB permeation flux against $(C_{Ef} - (P C_{Ep} / H_E))$. Since ETB has high Henry's law constant, permeation flux can be plotted verse C_{Ef} . Permeability can be related to overall mass transfer coefficient by the following equation (Hwang and She 2006):

$$Q_E = \frac{K_E \cdot C_{tot} \cdot l P_w^{sat}}{H_E} \quad (7)$$

In dilute PV, C_{tot} (total molar volume concentration of feed) is approximately equal to water molar volume density (mol/m^3). Since ETB has high Henry's law constant

t, permeate pressure has negligible effect on permeation flux (Equation 7). Therefore, for calculation of membrane permeability and overall mass transfer coefficient, ETB permeation flux can be plotted versus ETB mole fraction in the feed. The membrane permeability was calculated from the slope of regression line in Fig. 6. The results showed that the membrane permeability is about 2.36×10^{-8} (mol/m².s.Pa). Using Equation 7, the overall mass transfer coefficient is also about 1.018×10^{-6} (m/s).

According to resistance in series model, there are three resistances against mass transfer in the membrane process: feed, membrane and permeate resistances (Fig. 7a):

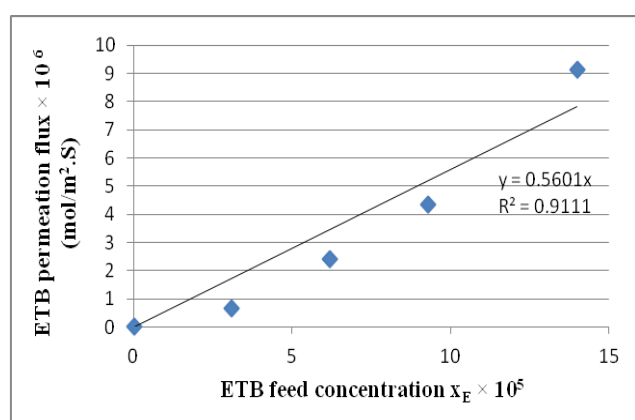


FIG. 6 ETB PERMEATION FLUX AS A FUNCTION OF FEED CONCENTRATION

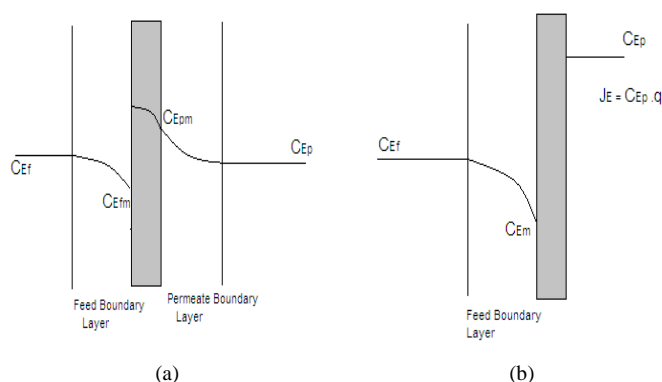


FIG. 7 SCHEM OF THE MEMBRANE MASS TRANSFER

$$\frac{1}{K_E} = \frac{1}{k_{El}} + \frac{1}{k_{Em}} + \frac{1}{k_{Eg}} \quad (8)$$

Where, K_{Eg} is the ETB mass transfer coefficient in permeate boundary layer. In PV of a dilute ETB aqueous mixture using synthesized PEBA membrane, the support layer and the permeate side resistances are negligible. The scheme of mass transfer in this case can

be presented according to Fig. 7b. Therefore, Equation 8 can be written as:

$$\frac{1}{K_E} = \frac{1}{k_{El}} + \frac{1}{k_{Em}} \quad (9)$$

The modified concentration polarization equation can be used for calculation of the membrane mass transfer coefficient and the boundary layer thickness. The simplified equation, for the non-ideal feed and high Henry's law constant, can be presented by the following equation (Hwang and She 2004):

$$\ln\left(\frac{1 - C_{Ef}/C_{Ep}}{1 - q/k_{Em}}\right) = -\left(\frac{\delta}{D_E}\right)q \quad (10)$$

Where, δ is the boundary layer thickness. The two unknown parameters (δ, k_{Em}) can be evaluated by the best fit method of the experimental data. The value of k_{Em} was initially estimated based on K_E and linear regression was used to calculate δ . The final value of k_{Em} was adjusted by the optimum value of the linear regression standard, R^2 (Hwang and She 2004).

The effect of permeate pressure on the membrane performance can be investigated by the following equation (Hwang and She 2004):

$$\frac{1}{\alpha} = \frac{1}{Q_r H_r} + \left(\frac{Q_r - 1}{Q_r H_r}\right) P_r \quad (11)$$

$$Q_r = \left(\frac{Q_E}{Q_w}\right) \quad (12)$$

$$H_r = \left(\frac{P_E^{sat} \gamma_E^\infty}{P_w^{sat}}\right) \quad (13)$$

$$P_r = \left(\frac{P}{P_w^{sat}}\right) \quad (14)$$

The reciprocal of separation factor ($1/\alpha$) versus relative pressure (P_r) is shown in Fig. 8. The relative membrane permeability (Q_r) and the relative Henry's law constant (H_r) were obtained by using slope and intercept of the plot. As calculated, Q_r is less than 1, which means that with decreasing permeate pressure ETB permeation flux increases with lower rate than water permeation flux (because of the higher ETB Henry's law constant).

The best-fit method using Equation 10 was used for calculation of the membrane mass transfer coefficient and the boundary layer thickness. Linear regression analysis for PV separation of ETB is shown in Fig. 9. The boundary layer thicknesses were calculated from the slope of the regression line. As calculated, the membrane mass transfer coefficient and the boundary layer thickness are 9.89×10^{-5} (m/s) and 7.4×10^{-4} (m), respectively.

The boundary layer mass transfer coefficient is also 1.02×10^{-6} (m/s) (as calculated using Equation 9).

The polarization index was also used to evaluate the concentration polarization phenomena. This parameter has numerical range from 0 to 1 and can be calculated using the following equation (Hwang and She 2006):

$$I = \frac{k_{El}}{k_{Em} + k_{El}} \quad (15)$$

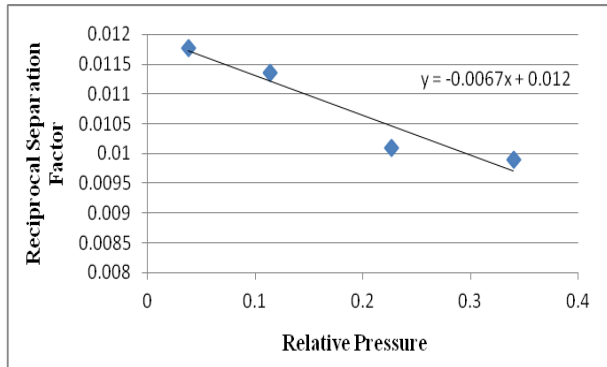


FIG. 8 RECIPROCAL SEPARATION FACTOR AS A FUNCTION OF RELATIVE PRESSURE

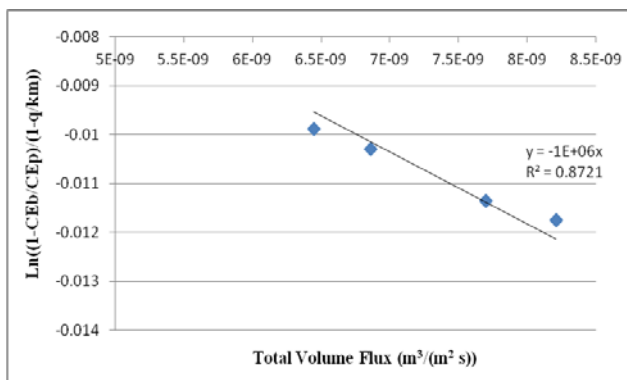


FIG. 9 LINEAR REGRESSION ANALYSIS FOR PV SEPARATION OF ETB

When, $I \approx 0$ and $I \approx 1$ concentration polarization is serious and neglectable, respectively. Using the mass transfer coefficients, the polarization index was calculated to be 0.01. This means that the concentration polarization is serious.

Modified Arrhenis Model

The relationship between permeation flux and feed temperature can be presented using the Arrhenius type formula [11]:

$$J_E = A' \exp\left(\frac{-E_{EP}}{RT}\right) \quad (16)$$

Where, A' , E_{EP} , T and R are correlation factor, PV activation energy, temperature and gas constant, respectively.

Another relationship between feed temperature and permeation flux can be described using activation

energy of the vapor pressure (E_{Ev}) and activation energy of membrane permeability (E_{Em}) (Hwang and She 2006):

$$\ln J_E = \ln J_{E0} - \frac{E_{Ev}}{R(T-C)} - \frac{E_{Em}}{RT} \quad (17)$$

$$\ln J_{E0} = \frac{\gamma_E^\infty x_E}{l} \exp(A + A_m) \quad (18)$$

Where, A' is correlation coefficient and A , B and C A, B, C are Antoine's constants.

E_{Ev} is positive and can be derived from the Antoine's equation (Hwang and She 2006):

$$\ln P_E^{sat} = A - \frac{B}{T-C} = A - \frac{E_{Ev}}{R(T-C)} \quad (19)$$

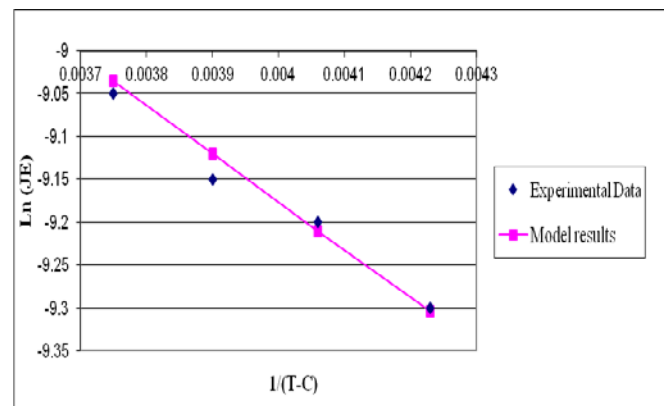


FIG. 10 MODIFIED ARRHENIUS RELATIONSHIP FOR ETB AT FEED CONCENTRATION OF 900 PPM

However, E_{im} can be positive, negative or zero and can be obtained from the Arrhenius type relationship (Hwang and She 2006):

$$\ln Q_E = A_m - \frac{E_{Em}}{RT} \quad (20)$$

E_{Ev} can be calculated using Equation 18 and E_{Em} can be obtained by correlating overall permeabilities with temperature (Equation 20). Equation 16 can be used to predict the model results.

The modified Arrhenius relationship can explain the effect of feed temperature on permeation flux.

The activation energy of vapor pressure for ETB and water are 26600 and 143900 J/mol.K, respectively. E_{Em} was obtained as -33262.6 J/mol.K for ETB. The experimental data and the model predictions are illustrated in Fig. 10. The experimental results and the model prediction values show good agreement and consistency.

Increasing feed temperature affects both sorption and diffusion. Diffusion coefficient increases with increasing temperature. On the other hand, ETB

solubility decreases with temperature because of the exothermic sorption process. Therefore, the extent of the temperature effect on sorption or diffusion determines the sign of the activation energy of membrane permeability. Increasing temperature increases ETB permeation flux due to increasing its driving force by affecting its vapor pressure. Therefore, the negative values of E_{Em} for ETB and water mean that the effect of temperature on sorption is greater than that on diffusion.

Conclusions

In this research, synthesis, characterization and performance of poly (ether block amide) membranes were studied. High quality membranes were obtained using a (3/1) ratio of iso- propanol / n-butanol, temperature range from 70-80 °C and polymer concentration range from 4-7 wt%. High performance was achieved for recovery of ETB from water with the PEBA membranes. It was observed that permeation flux and separation factor increase by increasing the ETB concentration in the feed. By increasing temperature and decreasing permeate pressure, permeation flux rises enhance but membrane selectivity diminishes. With decreasing permeate pressure, ETB permeation flux increase with lower rate than water permeation flux. Thus, ETB separation factor decreases by decreasing permeate pressure.

Mass transfer coefficients and boundary layer thickness were also calculated. It was found out that concentration polarization is almost serious.

Modified Arrhenius model was used to correlate ETB permeation flux and operate temperature. The results showed that the effect of temperature on sorption is greater than that on diffusion.

REFERENCES

- Cussler, E. L. "Diffusion Mass Transfer in Fluid Systems." third edition, University of Minnesota, Cambridge University Press, New York, 2007.
- Hwang, S. T. , and She, M. "Effects of concentration, temperature, and coupling on pervaporation of dilute flavor organics." *Journal of Membrane Science* 271 (2006): 16-28.
- Hwang, S. T., and She, M. "Concentration of dilute flavor compounds by pervaporation: permeate pressure effect and boundary layer resistance modelling." *Journal of Membrane Science* 236 (2004): 193-202.
- Jiraratananon, R., Sampranpiboon, P., Uttapap, D., Feng, X., and Huang, R.Y.M. "Pervaporation separation of ethyl butyrate and isopropanol with polyether block amide (PEBA) membranes." *Journal of Membrane Science* 173 (2000): 53-59.
- Jiraratananon, R., Chanachai, A., and Huang, R.Y.M. "Pervaporation dehydration of ethanol-water mixtures with chitosan/hydroxyethylcellulose (CS/HEC) composite membranes II. Analysis of mass transport." *Journal of Membrane Science* 199 (2002): 211-222.
- Li, L., Luo, Y., Tan, Sh., Wang, H., Wu, F., Liu, X., and Zhang, Z. "PPMS composite membranes for the concentration of organics from aqueous solutions by pervaporation." *Chemical Engineering Journal* 137 (2008): 496-502.
- Lyman, W. J., Reehl, W. F., Rosenblatt, G. H. "Handbook of Chemical Property Estimation Methods." American Chemical Society, Washington DC, 1990.
- Mohammadi, T., Kikhavani, T., and Moghbeli, M. "Synthesis and Characterization of Poly(ether block-amide) Membranes for Organic/Aqueous Mixtures." *Journal of Applied Polymer Science* 107 (2008): 1917-1923.
- Perry, R. H., "Chemical Engineer's Handbook", edited by Robert Perry, Mc Graw- Hill companies, 1999.
- Seaders, J. D. "Separation processes principles." John Wiley & sons publishing co., 1998.
- Sridhar, S., Smitha, B., Suhanya, D., and Ramakrishna, M. "Separation of organic-organic mixtures by pervaporation—a review." *Journal of Membrane Science* 241 (2004): 1-21.

Toraj Mohammadi Born in Iran in 1965, graduated as BSc from Abadan Institute of Technology, as MSc from Tehran University and as PhD from UNSW in 1995. He has been employed as Professor of Chemical Engineering in Iran University of Science and Technology, in addition, he has published more than 200 ISI papers, and supervised more than 150 MSc and 10 PhD students.



Tavan Kikhavani received her bsc in chemical engineering from tehran university (2003) and her msc from iust (2006). she has some publications in the area of membrane synthesis and is currently doing her phd at iust in the field of membrane separation processes.

Nomenclature

A	Antoine's constant
A_m	correlation coefficient in Arrhenius equation
B	Antoine's constant
C	Antoine's constant
C_{Ef}	ETB concentrations in the feed solution (mol/m ³)
C_{Ep}	ETB concentrations in the permeate (mol/m ³)
C_{Em}	ETB concentration within the membrane (mol/m ³)
D	Diffusion coefficient in aqueous solution (m ² /s)
E_{Em}	activation energy of membrane permeability for ETB (J/mol)
E_{Ev}	activation energy of vapor pressure for ETB (J/mol)
E_P	the activation energy of PV
H'	Partition coefficient
H	Henry's law constant
H_r	Relative Henry's law
J	Permeation flux
K_E	ETB Overall mass transfer coefficient (m/s)
k_{EL}	ETB mass transfer coefficient in liquid boundary layer (m/s)
k_{Em}	ETB mass transfer coefficient in membrane active layer (m/s)
k_{Eg}	ETB mass transfer coefficient in permeate layer (m/s)
l	membrane thickness
P	total permeate pressure (Pa)
P_E	partial permeate pressure of ETB (Pa)

P_w	partial permeate pressure of water (Pa)
P_{sat}	saturated vapor pressure (Pa)
P_r	Relative pressure
T	Temperature
Q	Overall permeability (mol/(m s Pa))
Q_r	Relative permeability
q	Total volume flux (m ³ /(m ² s))
R	Gas law constant
x	Mole fraction in liquid phase
y	Mole fraction in gas phase
Greek letters	
α	Separation factor
γ^∞	Activity coefficient in infinitely dilute aqueous solution
δ	Boundary layer thickness (m)
Subscripts	
E	ETB
W	Water
t	Total
f	Feed stream
m	membrane
P	permeate
l	Liquid boundary layer